

# An Integrated Research Plan for IFE Technology

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This article was submitted to  
International Atomic Energy Agency Technical Committee Meeting,  
Madrid, Spain,  
June 7-9, 2000

**June 2000**

U.S. Department of Energy

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# **An Integrated Research Plan for IFE Technology**

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## **Abstract**

In 1999, the U.S. Department of Energy's (DOE) Office of Fusion Energy Sciences (OFES) added an inertial fusion energy (IFE) element to its Virtual Laboratory for Technology (VLT). The scope of the IFE element of the VLT includes the fusion chamber, chamber/driver interface, target fabrication and injection, and safety and environmental assessments for IFE. Previous IFE power plant conceptual design studies identified many different driver/chamber/target options and the critical technical issues associated with them. Lawrence Livermore National Laboratory, in conjunction with other laboratories, universities and industry, has developed an R&D plan to address the critical issues in these areas in a coordinated manner. This paper provides an overview of the top-level critical issues and the current and proposed research activities to resolve them.

## **1. Introduction and Critical Issues**

Support for IFE within the US Department of Energy grew substantially in 2000. The majority of the OFES funded work is being devoted to R&D on heavy ion drivers, but nearly 20% is being devoted to the chamber and target technologies for both heavy ion and laser drivers. (Research on high-average-power lasers, which are potential IFE drivers, is currently funded by DOE Defense Programs.) Previous IFE power plant conceptual design studies identified many different driver/chamber/target options and the critical technical issues associated with them. Since it is not possible to consider all these options, current R&D in the U.S. is primarily focused on two of the most promising options. One is the renewable thick-liquid-wall chamber (e.g., HYLIFE-II) with indirect-drive targets and a heavy ion driver, and the other is the gas-protected, dry-wall chamber (e.g., Sombraero) with direct-drive targets and a laser driver [1,2].

During Phase-I (~4-5 years depending on budgeting), the R&D will be focused on the critical issues listed in Table 1 [3]. While all these issues will not be resolved during Phase-I R&D, the objective is to make significant progress in the resolution and show that credible pathways to resolution exist. Phase-I research will include assessment studies, small-scale experiments, and simulations. Later research will demonstrate more integrated (but still non-nuclear) chamber tests at closer to full scale. Information developed in Phase-I on chamber and target technologies, advances in driver designs and technology, and evolving target physics requirements for high gain, will be explored with integrated systems analysis in order to assess the overall feasibility and attractiveness of IFE. The small-scale experiments and integrated systems analysis may suggest alternative solutions to the direct- and indirect-drive approaches to IFE discussed above.

TABLE I CRITICAL ISSUES FOR CHAMBER AND TARGET TECHNOLOGY

Area	Critical Issues
Chambers - Thick-Liquid Wall - Dry-Wall	Protective liquid blanket formation, chamber clearing between pulses First wall protection, chamber lifetime
Driver/Chamber Interface - Ion Driver - Laser Driver	Magnet array design, placement, and shielding Final optics design and survivability
Safety & Environment	Accident consequences, tritium containment, end-of-life radioactive materials processing
Target Technology - Fabrications - Injection	Low cost, high-rate production Injector accuracy and reliability, target tracking, target survival

Activities in the U.S. that have begun to address these issues (including work at UC Berkeley, UCLA, UC San Diego, Georgia Institute of Technology, the University of Wisconsin, General Atomics, Lawrence Livermore National Laboratory, Los Alamos National Laboratory, and the Idaho National Engineer and Environmental Laboratory) will be reviewed.

## 2. Chamber Technologies

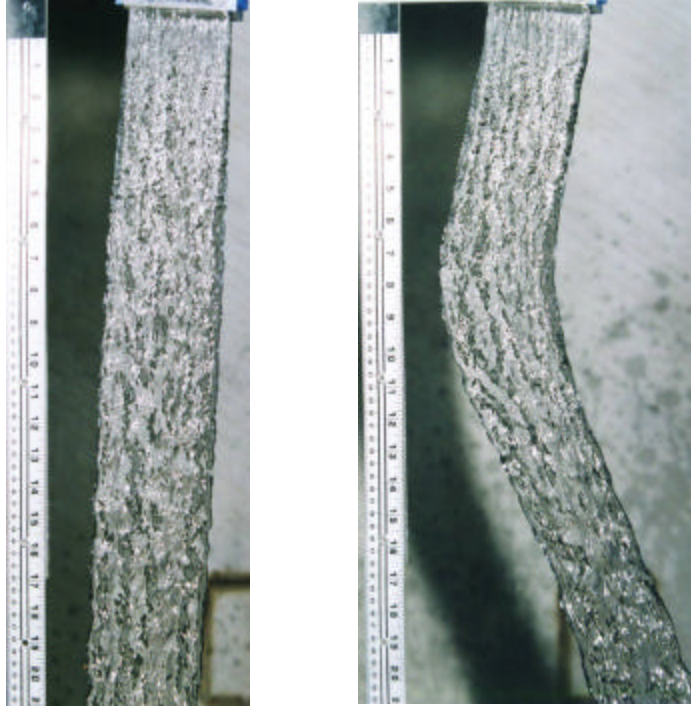
### 2.1 Thick Liquid Wall Chambers

Current work in this area is based on the HYLIFE-II chamber concepts, although concept development work on alternative liquid wall configurations is also ongoing. As noted in Table I, formation of the protective liquid blanket and chamber clearing between pulses (i.e., vapor condensation, droplet clearing and flow recovery) are the critical feasibility issues. The near term (~5 year) goal for research in this area is to develop convincing evidence from scaled experiments and modeling that the protective liquid pocket can be formed and that the chamber can be cleared between shots.

Several small-scale experiments on the characteristics of liquid jets are being conducted at UC Berkeley [4,5], UCLA [6], and Georgia Institute of Technology [7]. Two basic types of jet flow are required: 1) oscillating jets to form the thick liquid pocket around the target every pulse, and 2) steady-flow, sheet-jets that are arranged to form an array of ports for beam entry. The primary goals of these experiments are to 1) demonstrate that the liquid jet configurations required for the HYLIFE-II chamber can be established, 2) improve the quality of steady flow jets, and 3) demonstrate that the jet configuration can be re-established between pulses.

All three universities have conducted experiments on steady flow jets and means of improving jet quality through nozzle design and flow conditioning. Georgia Tech has also produced oscillating sheet jets that move in a pattern required by HYLIFE-II. The work at Georgia Tech is currently focused on characterizing and reducing surface ripple of the beam port jets using high Reynolds number water jets. This is important because the closer the jets can be positioned to the beam path, the more effective the neutron shielding will be. UCLA has been working with a low melting temperature (47 °C) liquid metal (Bi-Pb-In-Sn-Cd mixture). They have investigated the effects of nozzle design on jet quality and are using detailed numeric

simulations to predict flow features such as surface waves induced by orifice features. UC Berkeley has demonstrated the type of oscillating jet configuration required to form the protective pocket around the target. Figure 1 shows a steady flow jet and oscillating jet produced in the UCB flow facility [4]. Future work at UCB will utilize a series of chemical detonations to repeatedly disrupt a jet (or small array of jets) and then characterize the recovery [4]. UCLA is beginning experiments on Flibe vaporization and condensation using a plasma gun to simulate rapid vaporization in an IFE chamber.



*FIG. 1. Stationary (left) and oscillating (right) water jets at the UC Berkeley liquid hydraulic experimental facility. These jets are 1.6-cm thick and 8.0-cm wide at the nozzle.*

The R&D plan also calls for work on Flibe chemistry, efficient tritium recovery methods and removal of hohlraum materials from the Flibe, but this work has not yet been funded.

## 2.2 Dry-Wall Chambers

Currently planned R&D for dry-wall chambers is guided by the Sombrero, gas-protected chamber that uses a carbon-carbon composite first wall and blanket structure cooled by flowing  $\text{Li}_2\text{O}$  granules (this is also the breeding material). The key issues for this design, and any other dry-wall concept for that matter, relate to protection of the first wall and the lifetime of chamber structures. Several threats must be dwelt with: x-ray and debris damage to first wall must be prevented; the neutron damage life of the first wall and blanket structures must be acceptably long, probably at least one year depending on replacement time; possible erosion of the coolant channels by flowing granular coolant/breeder must be manageable or prevented. There is uncertainty in the data and analyses used to predict these effects, so one of the goals is to develop

a design that is tolerant of the range of uncertainties of surface ablation rates, thermal conductivity loss and swelling due to damage from neutrons, and heating from x-rays and target debris. The near term objective for work on dry-wall chambers is to conduct experiments and analysis to provide evidence supporting a wall life greater than one year.

The University of Wisconsin is taking the lead in assessments of dry-wall chambers. Their initial effort will focus on a reassessment of these issues based on information developed since the completion of the Sombrero study (1993). In the Sombrero design, the x-ray and debris energy is absorbed in a low density ( $<1$  torr) xenon gas, which then reradiates over a time longer than the burn time thus reducing the peak radiant heat flux to the first wall. Chamber dynamics modeling using the BUCKY code, predicts that the peak radiant heat flux is reduced from about  $2 \text{ GW/cm}^2$  to about  $35 \text{ kW/cm}^2$ . Experiments are needed to validate the gas opacity and radiation emission and transport. Experiments using Sandia National Laboratories' Z-machine have been proposed (but not yet funded) to examine vaporization of candidate first wall materials to help validate the various codes used to model chamber dynamics [8].

### **3. Chamber / Driver Interface**

#### **3.1 Ion-Driver / Chamber Interface**

Although the final focus magnets for a heavy ion driver are not in the direct line-of-sight of the fusion energy pulse, their interface with the fusion chamber is one of the key technology issues that needs to be addressed. Specifically, can superconducting final focusing magnet arrays be designed consistent with chamber and target solid angle limits for the required number of beams, standoff distance to the target, magnet dimensions and neutron shielding thickness?

The interface of the driver beams with the chamber present several challenges, particularly with current driver designs that have 100 beams or more. Figure 2 illustrates the liquid jets for chamber and beam port protection. This integration requires meeting constraints imposed by the target design (e.g., the acceptance angle of the beam relative to the target axis), the liquid wall shielding configuration, and heating and activation of the final focus magnets. The configuration of the shielding jets is given in [9]. The better the quality of the crossed shielding jets, the closer they can be position to the beam path and the more effective the radiation shielding will be. LLNL is leading efforts to continually integrate these and other power plant subsystems as new information on target and driver requirements become available.

Protecting the final focus magnets from radiation damage and heating is another important issue that is being addressed. A detailed 3D analysis of the final focus magnets and shielding has been completed [10]. This is preliminary work, and the design has not been optimized. The results indicate that more work is needed to extend the projected life of the magnets. Magnet heating does not appear to be a major concern. Subsequent work has focused on evaluating the effectiveness of additional shielding between the chamber and magnets, additional bore shielding, and various shield compositions. There is a trade-off here between the design for many beams to reduce the driver cost and the resulting reduction of space available for shielding. Another trade-off is that we would like to position the magnets close to the target to improve the ability to focus to small spot size, but this increases the radiation damage rates to the magnets.

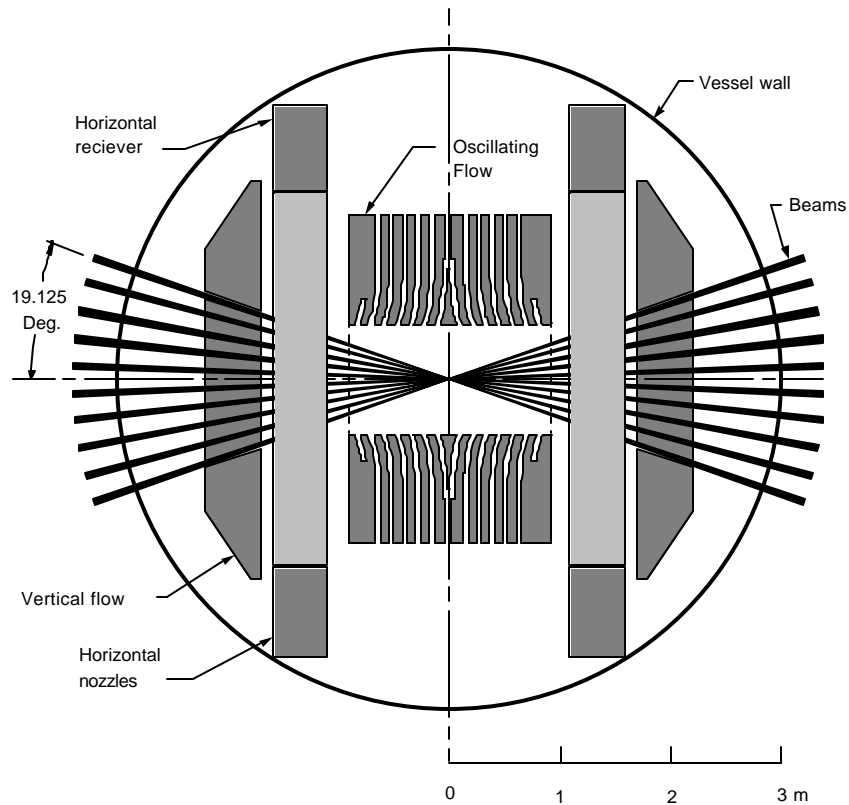


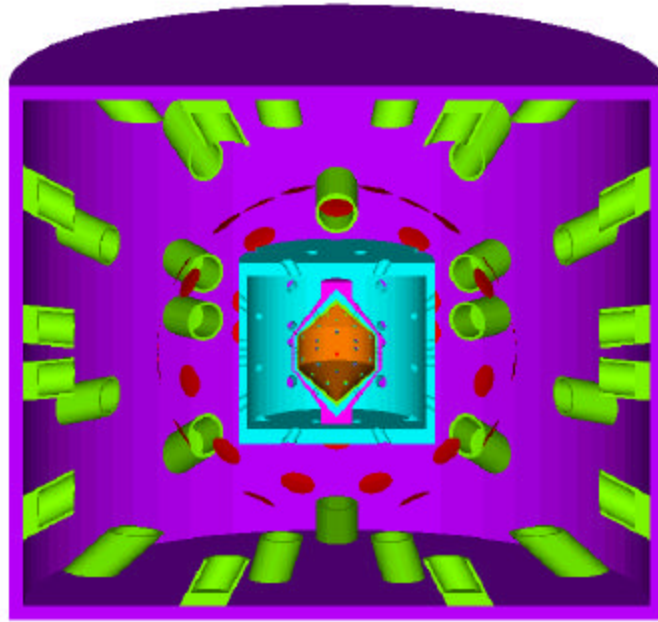
FIG. 2. HYLIFE-II chamber plan view. Oscillating jets surround the target and protect most of the chamber from line-of-sight neutrons. Crossing horizontal and vertical jets are used to allow beam entry while shielding the beam port region of the chamber.

### 3.2 Laser-Driver / Chamber Interface

While the final focus elements for a laser driver can be farther from the chamber center than the final focus magnets for an ion driver, the laser final optics will be in direct line-of-sight of the target emissions. The key issue is survivability of the final optics. Can they be adequately protected and/or made durable enough to withstand damage from laser light, neutrons, x-rays and debris and survive for more than one year before replacement? Also, will the final optics have sufficient mechanical stability under pulsed heating and possible gas shocks to maintain the required pointing accuracy for target tracking?

Concepts for protecting final optics and making them more damage tolerant have been proposed, but experimental data and development are needed. One idea is to use fused silica that runs hot enough that radiation damage is expected to anneal. Additional radiation damage studies of hot-fused silica and other optical materials (e.g., calcium fluoride) have been proposed, but current funding is inadequate to complete these. Analysis of grazing incidence metal and liquid-metal mirrors (GIMMs and GILMMs) shows that these are possible solutions. The University of California at San Diego now has a 2 J laser test facility, and they will be testing laser damage threshold for GIMMs and also schemes for protecting the mirrors. The University of Wisconsin has proposed using its shock tube to address the issue of gas shocks on final optics. Detailed 3D neutronics analyses (see Fig. 3) have been completed for the Sombrero power plant using a

direct-drive target and a diode-pumped solid state laser to determine neutron and gamma fluences and doses in the final and penultimate optics [11]. Data is needed, however, to estimate the lifetime of these components.



*FIG. 3. A three-dimensional neutronics model of the Sombrero chamber, final optics and reactor building. Neutron dumps located on the building wall reduce the radiation dose to penultimate optics (not shown).*

#### **4. Safety and Environmental**

Favorably resolving safety and environmental (S&E) issues will be a key factor in the success of fusion energy. In order for fusion to achieve its full potential for S&E advantages over competing energy sources, it is essential that analyses are performed early in the design of any facility so that wise choices can be made and lessons learned from previous designs incorporated. One key issues is plant safety during normal operation and in the event of possible accidents. The objective is to design plants that have a level of safety consistent with no-public-evacuation-plan requirement ( $<1$  rem site boundary dose) for credible accident scenarios and resultant radioactivity releases. Tritium inventory and containment are issues that require special attention in the design. The key environmental issues are related to end-of-life materials processing. The degree to which materials can be recycled and the trade-offs between radioactive waste volume and hazard level are important factors in this area.

Currently two national labs, INEEL and LLNL, lead the S&E work for IFE. Over the past year the codes that were developed to carry out safety analyses for magnetic fusion energy (MFE) power plants have been adapted to study IFE. The first safety analysis of HYLIFE-II using these adapted models was recently completed [12]. The results of the safety analysis are quite encouraging, giving a site boundary dose below 0.5 rem for a severe accident scenario.

This is low enough to avoid the need to have an evacuation plan for the plant, which is one of the goals of the S&E effort. Work has now started on analyses for the Sombrero power plant design.

Another recent activity has been a survey of elements that are most favorable for target fabrication from the point of view of activation. This work is presented in [13]. Some of the best candidates include Hg and Pb. Both are acceptable from the target physics point of view, with a ~ 10% decrease in target gain compared to targets using Au-Gd, a typical high-Z mixture used in target physics calculations. Another important consideration will be the effect that these materials have on the Flibe chemistry. This work has been prospered but is not yet funded [3].

INEEL is planning experiments with Flibe and SnLi, a possible alternative liquid wall candidate. The Fusion Liquid Release Experiment (FLIQUER) will look at mobilization of Flibe constituents that have been exposed to a radiation source. INEEL will also be characterizing the vapor constituents and vapor pressure of both Flibe and SnLi. This information will be used to provide more accurate radioactive source terms for the safety calculations.

## **5. Target Fabrication and Injection**

As noted in Table 1 the key issues here are production of targets at low cost and the ability to inject them without damage to the fragile fuel capsule. R&D on Target fabrication and injection must address several key questions. Can direct and indirect-drive targets be mass produced with the required precision at an acceptable cost (~ 0.3 U.S. dollars each)? Can these targets withstand the mechanical and thermal loads during acceleration and transit through the chamber? Can injection, tracking and triggering be sufficiently predictable? The two principal institutions working in this area are General Atomics (focusing on injection) and Los Alamos National Laboratory (focusing on target materials and fabrication techniques). This topic is covered in more detail in [14]. It is important to note, however, that the target technology work is being closely integrated with the chamber design and S&E work.

## **6. Systems Studies**

It is important that as we proceed with addressing and resolving the key issues for the various chamber and target technology subsystems, the solutions are continually integrated to assure that the interface constraints are met, trade-off comparisons made and future direction defined. A good example of the need for an integrated effort has to do with target designs. The high-Z materials used in indirect-drive targets (radiators and hohlraums) are initially proposed by target designers based on their atomic physics properties. The choice of the material, however, will also affect several other plant systems. Since the high-Z materials gets in the Flibe used in the thick liquid wall chamber, they must be easily recovered and not adversely effect the system chemistry. Some choices can have undesirable safety and environmental characteristics. Finally, the materials must be suitable for mass manufacture at low cost.

Results must also be integrated with results from R&D on target physics and driver technologies. The ARIES Team will play a key role in this, adding to the ongoing integration efforts of the IFE element of the VLT. ARIES work on IFE is beginning in the summer of 2000 and is expected to continue for at least 16 months. The ARIES work and coordination through

the IFE element of the VLT, will help assure that the groups working on the different aspects of IFE interact and attempt to resolve conflicting trade-offs and develop self-consistent designs that meet performance and attractiveness goals.

## 7. Conclusions

An R&D plan for IFE chamber and target technologies has been developed to help coordinate efforts in this area. Current activities are focused on addressing key feasibility issues. Work includes both small-scale experiments and modeling by national laboratories, universities and industry. This work, in combination with success in target physics and driver performance, will set the stage for proceeding with the next steps in the development of IFE.

## Acknowledgements

The author would like to acknowledge the contributions of colleagues participating in the IFE chamber and target technology work at General Atomics, Georgia Institute of Technology, Idaho National Engineering and Environmental Lab, Lawrence Livermore National Laboratory, Los Alamos National Lab, UC Berkeley, UCLA, UC San Diego, and the University of Wisconsin. This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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